

Iron Air collision with high density QCD

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The color glass condensate approach describes successfully heavy ion collisions at RHIC. We investigate Iron-air collisions within this approach and compare results to event generators commonly used in air shower simulations. We estimate uncertainties in the extrapolation to GZK energies and discuss implications for air shower simulations.

1. Introduction

Higher twist corrections to hadronic interactions become increasingly important at high energies. An effective way to resum all these contributions is the color glass condensate picture. We review the Kharzeev-Levin-Nardi (KLN)[1] approach to heavy ion collisions, which has successfully been applied to RHIC physics, and extrapolate this model to Iron-air collisions at energies up to the GZK ($\approx 10^{19.7}$ eV) cutoff. So far, we only calculate multiplicities. In the near future, we hope to present a full model which also treats the forward scattering in detail, which is important for air showers.

2. Review of BBL 1.0

In Ref. [2] we introduced the black body limit (BBL) model for hadron-nucleus reactions. Valence quarks scatter coherently off the gluon field in the target. The transverse momentum acquired in this reaction is of the order of the saturation momentum, defined by the density of gluons in the target. This leads to independent fragmentation of the leading quarks at high energies, when the saturation momentum is high. The leading baryon effect known from lower energies is suppressed.

Gluon production in this approach is realized within the KLN model: a simple ansatz for the unintegrated gluon distribution function (uGDF) is applied to the k_t -factorization formula. In this paper, we apply this model to Iron-air collisions.

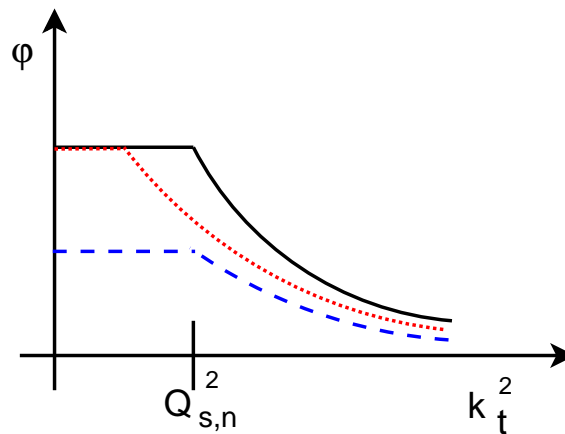


Figure 1. The construction of the uGDF for low densities. The full line shows the uGDF of a single nucleon. The dashed line is the average uGDF for $p_A \approx 0.5$. The dotted line shows the uGDF for the averaged low density.

3. KLN approach to nucleus-nucleus collisions

In the k_\perp -factorization approach [3], the distribution of produced gluons is given by

$$\begin{aligned} \frac{dN_g}{d^2r_\perp dy} &= \frac{4N_c}{N_c^2 - 1} \int_{p_\perp^{\min}}^{p_\perp^{\max}} \frac{d^2p_\perp}{p_\perp^2} \int^{p_\perp} d^2k_\perp \alpha_s \\ &\times \phi_A(x_1, k_\perp^2) \phi_B(x_2, (p_\perp - k_\perp)^2) \quad (1) \end{aligned}$$

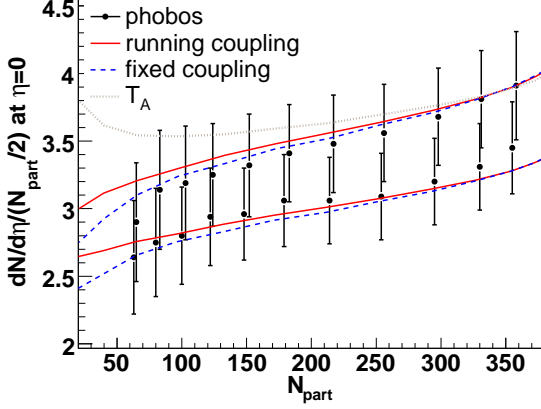


Figure 2. The multiplicity of charged particles as a function of the centrality. The grey dotted line shows the result when taking Q_s^2 to be proportional to the average density T_A . The data is from PHOBOS [5].

with $N_c = 3$ the number of colors. Here, p_\perp and y denote the transverse momentum and the rapidity of the produced gluons, respectively. The light-cone momentum fractions of the colliding gluon ladders are then given by $x_{1,2} = p_\perp \exp(\pm y)/\sqrt{s}$, where \sqrt{s} denotes the center of mass energy and y is the rapidity of the produced gluon. We set p_\perp^{\max} such that the minimal saturation scale $Q_s^{\min}(x_{1,2})$ in the above integration is $\Lambda_{QCD} = 0.2$ GeV.

The KLN approach [1] employs the following uGDF:

$$\phi(x, k_\perp^2; r_\perp) \sim \frac{1}{\alpha_s(Q_s^2)} \frac{Q_s^2}{\max(Q_s^2, k_\perp^2)}, \quad (2)$$

where Q_s denotes the saturation momentum at the given momentum fraction x and transverse position r_\perp . The overall normalization is determined by the multiplicity at mid-rapidity for the most central collisions. The saturation scale for nucleus A is taken to be proportional to the density of participants, $n_{\text{part}}^A(r_\perp)$. This is not a universal quantity which depends only on the properties of a single nucleus, in other words, the uGDF is not fully factorizable.

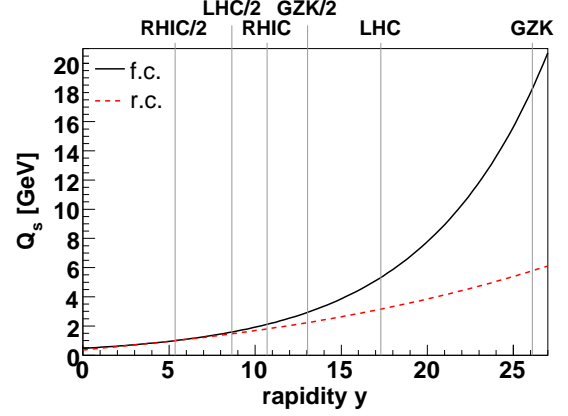


Figure 3. The saturation scale as a function of the rapidity $y = \log(1/x)$. The vertical lines denote the forward and mid-rapidity regions for the different energy regions.

A possible solution seems to be to define the saturation momentum squared to be proportional to $T_A(r_\perp)$, which is dependent on one nucleus only and therefore respects factorization. However, this ansatz cannot describe the data on the multiplicity as a function of centrality for Au-Au collisions at RHIC, as shown in Fig. 2. Why this does not work can best be seen with the following example. We consider a peripheral Au-Au collision, and want to construct the uGDF at the edge of one of the nuclei. Here, T_A is very small, which means that only in some nucleus configurations, we actually find a nucleon at this position. Let us denote the probability to find (at least) one nucleon with p_A . The uGDF at this position is then p_A times the uGDF of a single nucleon, as sketched in Fig. 1 (dashed line). Taking the average density T_A would lead to the dotted line, and gives the wrong uGDF, since averaging has to be done after constructing the wave function and not before. The density under the condition to find at least one nucleon is T_A/p_A , see [4] for details. The saturation scale is therefore:

$$Q_{s,A}^2(x, r_\perp) = 2 \text{ GeV}^2 \left(\frac{T_A(r_\perp)}{1.53 p_A(r_\perp)} \right) \left(\frac{0.01}{x} \right)^\lambda \quad (3)$$

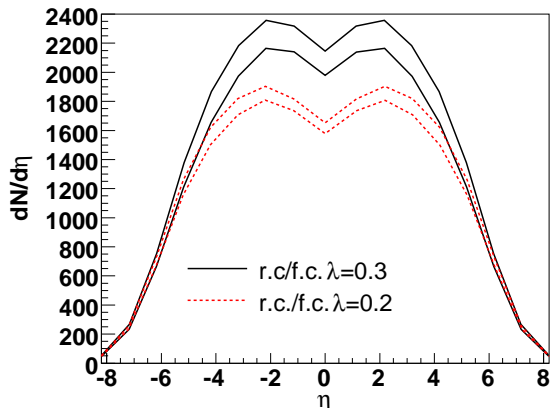


Figure 4. The rapidity dependence of the multiplicity for central ($b = 2.4$ fm) Pb-Pb collisions at the LHC.

and the ansatz for the uGDF is

$$\phi_A = p_A \phi \left(\frac{T_A}{p_A} \right). \quad (4)$$

In Ref. [4] we explain that the multiplicity is a homogeneous function of order one in the density of both nuclei, and the n_{part} description is a good approximation of the factorized KLN approach.

4. Results

Before showing some results and extrapolating to high energies we want to discuss the evolution of the saturation scale as a function of the energy. Fig. 3 shows Q_s as a function of the rapidity for fixed coupling and running coupling evolution. See Ref. [2] for details on these two types. The two evolution types show large differences at forward rapidity for LHC and GZK energies. Differences at mid-rapidity for RHIC and LHC are however less significant. Therefore, fixed and running coupling predict very similar results for RHIC and LHC overall multiplicities.

4.1. Accelerator Results

Very good agreement with the data from the PHOBOS collaboration [5] is shown for the multiplicity at mid-rapidity as a function of centrality,

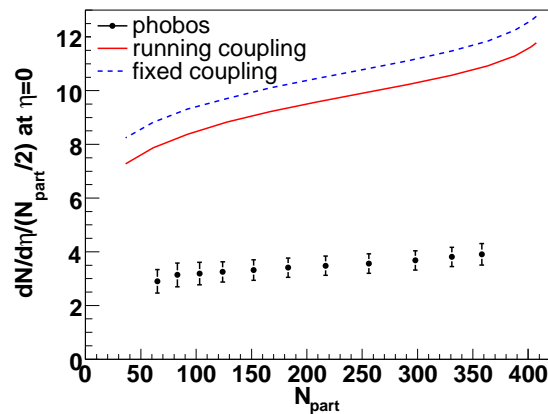


Figure 5. The multiplicity of charged particles as a function of the centrality for a 5500 GeV Pb-Pb collision at the LHC ($b=2.4$ fm). The upper curve for each λ shows fixed coupling, the lower curve shows running coupling evolution.

as shown in Fig. 2. As already stated, the differences between fixed and running coupling evolution are small.

In Fig. 4 we see predictions for central ($b=2.4$ fm) Pb-Pb collisions at the LHC ($\sqrt{s} = 5500$ GeV). The centrality dependence of the multiplicity at mid-rapidity is shown in Fig. 5.

4.2. Iron Air

Fig. 6 shows the rapidity dependence of charged particles for central Iron-Nitrogen collisions at the three reference energies for RHIC, LHC and GZK (200 GeV, 5500 GeV and 400 TeV, respectively). Up to LHC energies, differences at mid-rapidity are smaller than 15%. Only at GZK energies, we see a qualitative difference.

Fig. 7 shows the total multiplicity of charged particles as a function of the lab-energy per nucleon. Since in cosmic ray physics the energy of a nucleus is usually the total energy, plotting E_{lab}/A is a useful quantity when comparing to proton-air collisions. We also compare to the standard hadronic interactions models Sibyll 2.1 [6] and QGSJET-IIc [7]. First, we observe that nucleus air collisions in Sibyll are obtained by su-

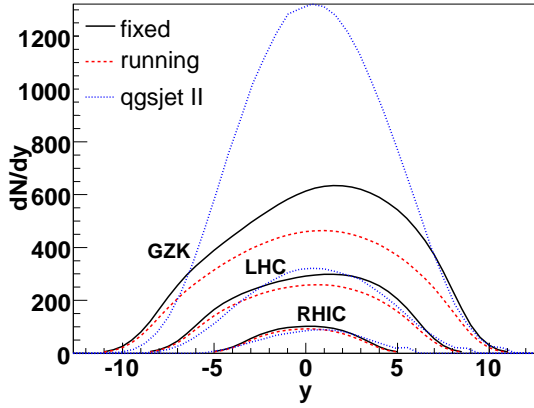


Figure 6. The rapidity dependence of charged particles for central Fe-N collisions at the three reference energies. The results for QGSJET-II and KLN (fixed and running coupling evolution) are shown.

perposition of hadron air collisions. The multiplicity scales therefore with the number of participants in the projectile and ranges from a factor 30 to 36 compared to proton air collisions. In the QGSJET-II model and the KLN approach, screening in the initial state reduces the multiplicity. The predicted results of these two approaches are quite similar up to LHC energies, whereas above this energy, QGSJET-II predicts higher multiplicity than the color glass approach (running coupling evolution).

4.3. Conclusions

We compared the multiplicities of Iron-air collisions in the color glass condensate approach (KLN model) with hadronic interaction models used in air shower simulations. The results of QGSJET-II and KLN are quite similar up to LHC energies. Above this energy, QGSJET-II predicts higher multiplicities.

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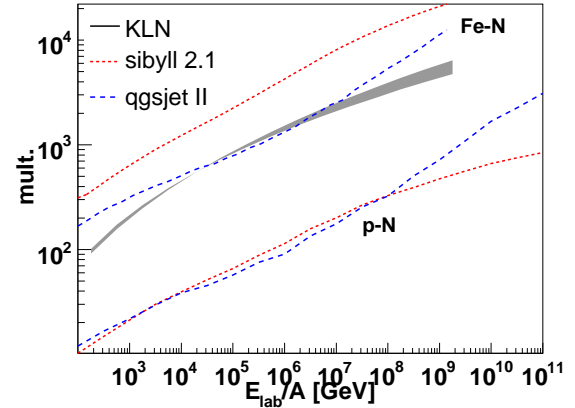


Figure 7. The total multiplicity of charged particles as a function of the energy (in the laboratory frame) per nucleon. Sibyll predicts a higher multiplicity, since it is a superposition model and scales with the number of participants in the Iron nucleus as compared to p-air collision. QGSJET-II and the color glass approach predict similar multiplicities up to LHC energies.

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